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# SHOCK TUBE TEST FOR ENERGY ABSORBING MATERIALS

**by**
**John Fitek**

September 2013

Final Report
October 2011 – October 2012

**Approved for public release; distribution is unlimited**

**U.S. Army Natick Soldier Research, Development and Engineering Center**
**Natick, Massachusetts 01760-5020**

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**14. ABSTRACT**
This report describes the redesign and demonstration of an experiment, developed by the Natick Soldier Research, Development and Engineering Center (NSRDEC), to measure the response of energy absorbing materials behind a buffer material, loaded with the shockwave and dynamic pressure pulse in a shock tube. This test has application in the development of body armor for blast attenuation and impact attenuation. Foam materials are rapidly compressed between the striker (buffer) and fixed test plate at dynamic strain rates reaching peak levels between 500-1000/s. Foam stress is calculated by measuring the reaction force of the material with a dynamic load cell. Foam compression is measured through high speed video image analysis. With the current experimental set-up, the material test results are very similar to those obtained with a drop weight impact test.

**15. SUBJECT TERMS**

| | | | | |
|---|---|---|---|---|
| FOAM | DROP TESTS | IMPACT TESTS | STRAIN(MECHANICS) | IMPACT ATTENUATION |
| BLAST | ABSORPTION | ATTENUATION | DYNAMIC RESPONSE | TEST AND EVALUATION |
| BUFFERS | BODY ARMOR | TEST METHODS | FOAMED MATERIALS | ABSORBERS(MATERIALS) |
| VELOCITY | SHOCK TUBES | LOADS(FORCES) | ENERGY ABSORPTION | |
| PRESSURE | SHOCK WAVES | SHOCK(MECHANICS) | ENERGY ABSORBING MATERIALS | |

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# SHOCK TUBE TEST FOR
# ENERGY ABSORBING MATERIALS

## 1 Introduction

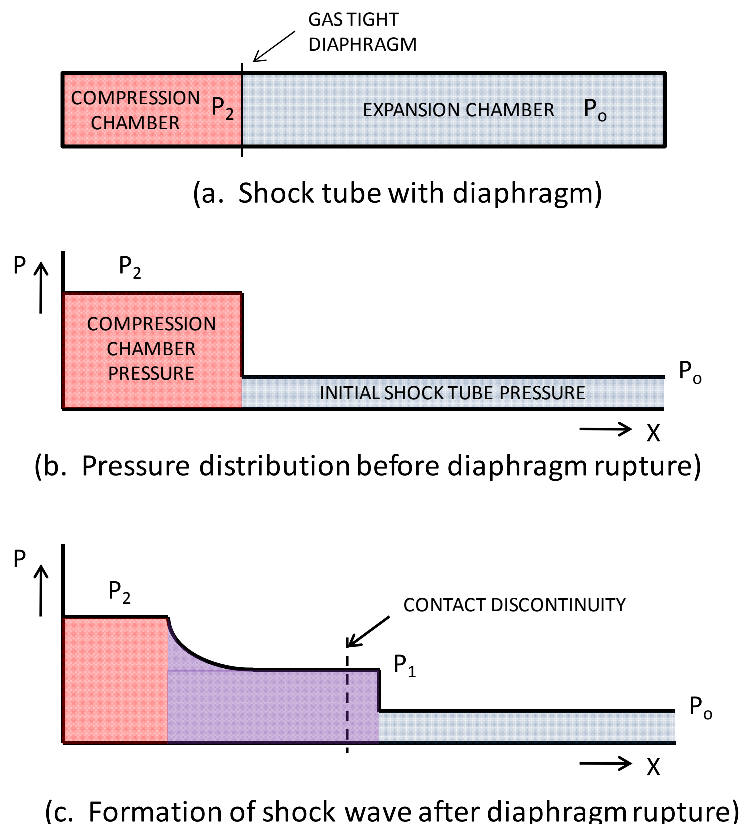
This report describes work performed by the Natick Soldier Research, Development and Engineering Center (NSRDEC), between October 2011 and October 2012, to develop and demonstrate a test for energy absorbing materials and to redesign the equipment and setup used. The test measures the response of energy absorbing materials behind a buffer material loaded with the shockwave and dynamic pressure pulse in a shock tube, and it has application in the development of body armor for blast attenuation and impact attenuation. The test demonstration utilized the NSRDEC shock tube for blast research (1) configured for material testing purposes.

The redesigned test equipment and set-up were developed to resolve problematic issues with previous shock tube material testing work at NSRDEC (2). The redesign enables calculation of foam stress by measuring the reaction force of the material with a dynamic load cell and measurement of foam compression through high speed video image analysis. This project was conducted in parallel with the redesign and demonstration of a drop weight impact test for energy absorbing materials (3). The drop test results are presented in this report and are compared with shock tube results for several materials of interest for impact attenuation.

# 2 Background and Theory

## 2.1 *Shock Tube Experiment*

The shock tube is an experiment commonly used to study shock waves and blast waves. The shock tube consists of a compression chamber and an expansion chamber, initially separated by a diaphragm, as shown in Figure 1a. The compression chamber is pressurized (Figure 1b) until the diaphragm ruptures. The pressurized gas from the compression chamber is then released into the expansion chamber. A shock wave is formed as the pressurized gas propagates into the expansion chamber. This initial shock wave formation in the shock tube is shown in Figure 1c.




Adapted from (3)

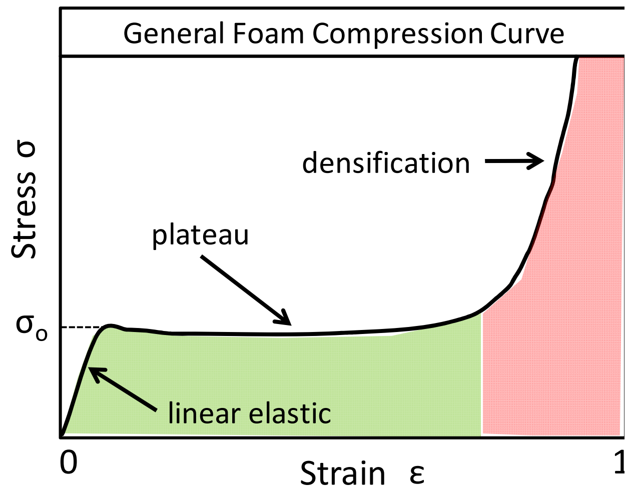
**Figure 1. Diagram of shock tube theory**

The NSRDEC shock tube has a compression chamber (driving section) length of 305 mm, an expansion chamber (driven section) length of 1830 mm, and an inside diameter of 67.2 mm (1). It is constructed of schedule 20 stainless steel pipe.

If the end of the shock tube is blocked with a flange or other obstruction, the shockwave will reflect off the obstruction and propagate in the opposite direction (back up the tube). During the reflection, there is a superposition of the incident and reflected waves, which can be more than twice the pressure of the incident wave (4). The shock tube test for energy absorbing materials uses this effect to apply an impulsive force to a buffer material (striker), which rapidly compresses a test specimen of energy absorbing foam.

## 2.2 *Energy Absorbing Foam Materials*

Foam is a cellular material which has the ability to deform at a relatively low stress level and absorb energy. Foam is used in protective applications to prevent an object from exceeding a maximum acceleration limit. An example is the use of foam material to package a fragile product for shipment. Foam materials can reduce peak acceleration by reducing the peak force on an object and increasing its duration over time (5). A general stress vs. strain compression curve for a foam material is shown Figure 2. This diagram shows the three distinct regions of cellular structure response: linear-elastic, plateau, and densification (6).




Adapted from (5)

**Figure 2. General stress vs. strain response of a foam material**

Foam can provide protection from an impact load by absorbing energy through foam compression in the constant stress plateau region, highlighted in green in Figure 2. The energy absorbed by the foam during impact is equal to the force integrated over the foam compression. The foam thickness must be sufficient to absorb the energy of the impact in the plateau region, without compression into the densification region of the foam stress vs. strain curve. The shock tube test for energy absorbing materials is designed to test materials that can absorb a significant amount of energy per unit volume at a relatively low stress level.

# 3 Redesign of Experimental Set-up and Procedures

Structural support and mass were added to the material testing fixture, using steel vises and a steel anvil, to reduce motion of the shock tube and test specimen. A dynamic load cell was incorporated to measure the reaction force of the foam test specimen, in place of a pressure sensor which only measured contact pressure at one point. The buffer material was designed as a plug shaped striker, which is guided by the shock tube as it compresses the test specimen. This experimental set-up allows the test specimen to be placed outside the shock tube so the foam compression can be measured using high speed video analysis. The shock tube driven end and material test fixture are shown in Figure 3.

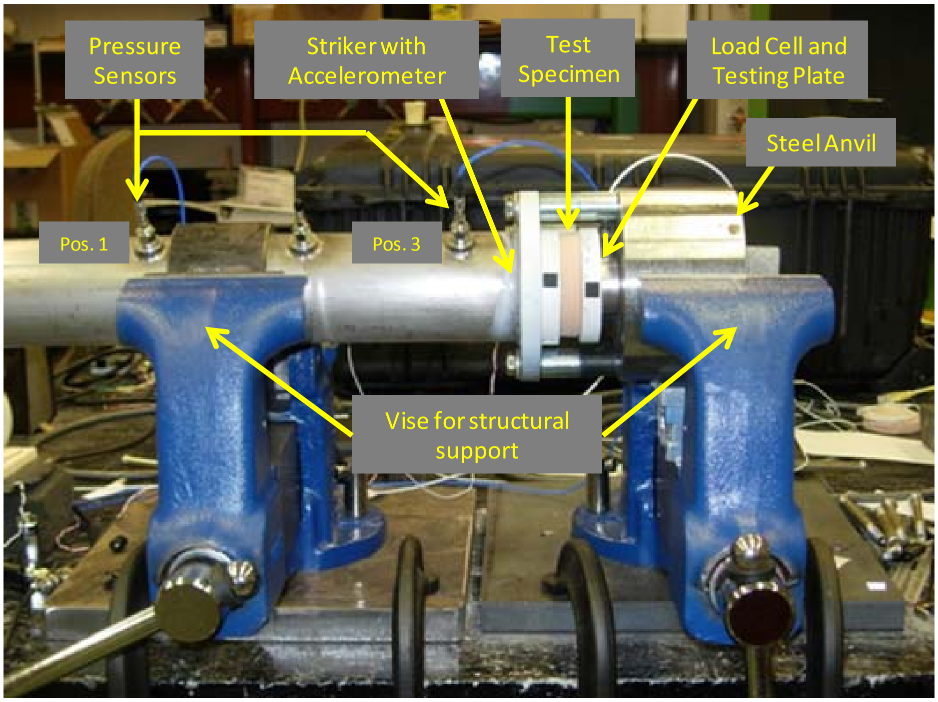



**Figure 3. Shock tube material test fixture and support apparatus**

The redesigned striker is shown in Figure 4. The 50 mm thick smaller diameter section (67 mm outside diameter) fits into the end of the shock tube, and the shoulder of the larger diameter section (25 mm thick, 76.2 mm outside diameter) sits against the shock tube end flange. The striker assembly contains an internally mounted accelerometer.

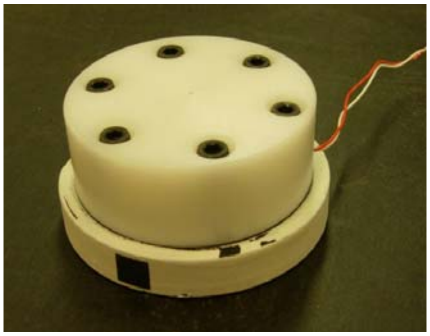


**Figure 4. Shock tube material test striker**

The striker fits into the end of the shock tube as shown in Figure 5. During the test, the shock tube pressure forces the striker out of the tube and compresses the foam test specimen (visible in orange/pink color). The reaction force is measured by the load cell between the steel test plate and the anvil. The compression of the foam is measured by tracking the difference in position between the two black boxes using high speed video analysis. It is necessary to track the motion of the steel test plate because, despite the efforts to add mass and structural rigidity to the system, there is still a small amount of motion in the fixture during the impact test, which must be accounted for in the data analysis.

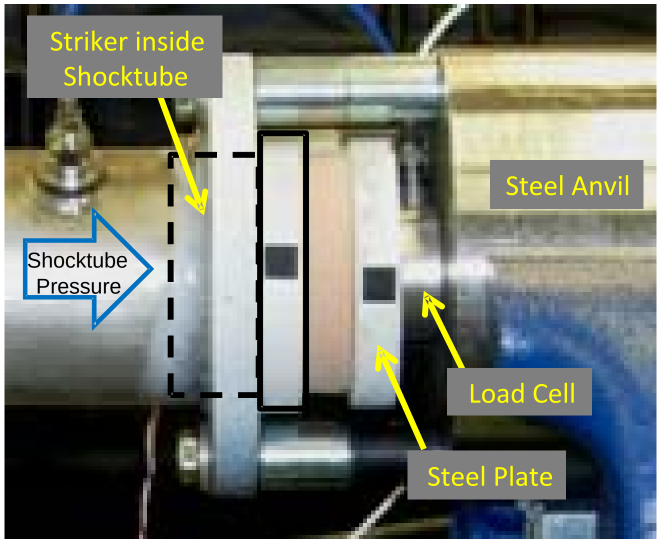



**Figure 5. Striker location in shock tube**

The high speed video camera and lighting arrangement are displayed in Figure 6. In addition to measuring foam compression through video image analysis, the high speed video allows for experimental observations in an impact test where they would otherwise be impossible.

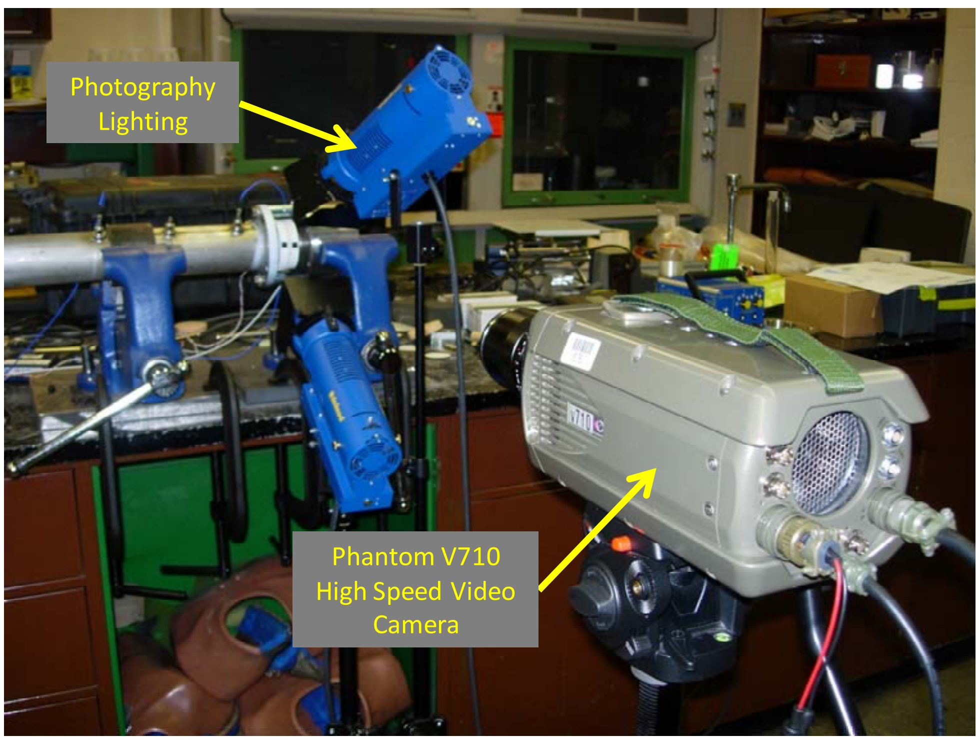



**Figure 6. High speed video camera set-up**

The compressed air tank and air pressure regulator are shown in Figure 7, with the shock tube driver section. A diaphragm of polyester sheet material was assembled between the flanges of the shock tube driver and driven sections. To run the test, a valve is opened by hand to pressurize the driver section until the diaphragm ruptures, which initiates the formation of a shockwave and dynamic pressure pulse in the driven section of the shock tube.

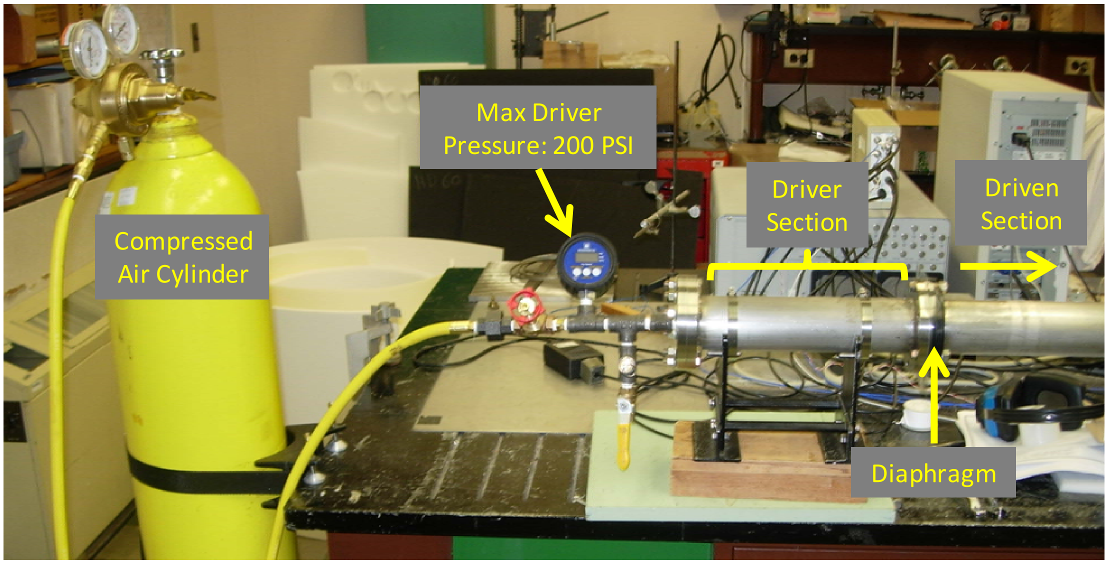



**Figure 7. Compressed air driver section**

Table 1 lists and describes the data acquisition equipment and sensors.

**Table 1. Shock tube material test data acquisition and sensor information**

| | |
|---|---|
| Striker Material<br>Striker Face Diameter<br>Striker Mass | Nylon<br>76.2 mm<br>7.3 kg |
| Specimen Diameter | 68 mm +/- 1mm |
| Data Acquisition Sys.<br>Data Sampling Rate | Win 600<br>2 MHz |
| Total data acquired<br>Pre-Trigger | 64K: 32.77 ms<br>7.94 ms |
| Triggering | Trigger circuit senses shocktube pressure rise and simulatneously triggers DAQ and Camera |
| High Speed Video Camera<br>Frame Size<br>Frame Rate | Vision Research Phantom V710<br>512 X 512<br>25K frames/sec. |
| Dynamic Load Cell<br>Load Cell Capacity | PCB 200C20<br>0 - 88.96 kN (20,000 lbs) |
| Accelerometer<br>Accelerometer Range | PCB 350B02<br>50K g |
| Signal Conditioner | PCB Model 482A22 |

# 4 Materials Tested

In this study, a variety of foam materials were tested with the shock tube. They are listed in Table 2 with their characteristics and test specimen dimensions. These products were chosen as part of a study of materials for an impact attenuating helmet liner project (3).

Table 2. Foam materials for testing (7) (8) (9)

| **Manufacturer** | **Foam** | **Type/ID** | **Flexibility** | **Polymer Material** | **Energy Absorption Mechanism** | **Density** | | **Quasi-Static Comp Strength** (MPa) | **Specimen Thickness** *(mm)* | **Specimen Diameter** *(mm)* |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *kg/m* | *lb/ft* | | | |
| Evonik | ROHACELL | 31A | rigid | Polymethacrylimide | brittle fracture | 32 | 2.0 | 0.40 | 12.8 | 45.8 |
| Evonik | ROHACELL | 51A | rigid | Polymethacrylimide | brittle fracture | 52 | 3.2 | 0.90 | 12.8 | 68.0 |
| Zotefoam | PLASTAZOTE | HD60 | semi-rigid | HD Polyethylene | elastic/plastic | 60 | 3.7 | 0.35 | 12.5 | 67.7 |
| Zotefoam | PLASTAZOTE | HD80 | rigid | HD Polyethylene | elastic/plastic | 80 | 5.0 | 0.50 | 15.5 | 48.2 |
| Zotefoam | PLASTAZOTE | HD115 | rigid | HD Polyethylene | elastic/plastic | 115 | 7.2 | 0.80 | 15.4 | 48.2 |
| Zotefoam | PLASTAZOTE | LD70 | flexible | LD Polyethylene | elastic/plastic | 70 | 4.4 | 0.20 | 13.1 | 69.0 |
| Team Wendy | Zorbium | Z110 | flexible | HD Polyethylene | viscoelastic | 54 | 3.4 | 0.07* | 12.5 | 67.9 |

* Highly rate dependent

ROHACELL® is a rigid and lightweight foam material with a closed-cell structure, and a very high strength-to-weight ratio (7). It is commonly used as a sandwich composite core in the aerospace industry. PLASTAZOTE® materials are closed cell polyethylene foams, commonly used for protective equipment for sports, including application in helmet liners (8). Zorbium™ is the viscoelastic polyurethane foam used in military helmet suspension system pads (9).

# 5 Results and Discussion

Section 5.1 presents detailed data from the shock tube test of the PLASTAZOTE HD60 material to demonstrate the shock tube material test and data analysis techniques. Section 5.2 presents and compares stress vs. strain data for all the materials tested with the shock tube. Section 5.3 compares data from several materials (ROHACELL 51A, PLASTAZOTE HD60, and Zorbium 110i) tested with the shock tube to the data for those same materials from the drop tests conducted during the helmet liner project (3). These materials were selected for comparison to highlight the similarity in results between the shock tube and drop test for three very different foam materials.

## 5.1 *Demonstration of Shock Tube Test and Analysis Techniques Using HD60 Data*

During the demonstration test, the shock tube generated a pressurized pulse of air which acted on the striker and compressed the foam material. The shockwave and dynamic pressure pulse was measured at the position 1 and 3 pressure sensors. It is plotted for the HD60 foam test in Figure 8. The upper plot displays the pressure wave for 10 ms, and the lower plot shows only the first 3 ms. There are two steps in the pressure traces shown in Figure 8, observed most clearly with the upstream (position 1) sensor data. The first step is the incident pressure wave as it travels down the shock tube towards the striker/ test specimen. The second step is the reflected wave as it travels in the opposite direction, away from the striker. The measured pressure after the second step is the superposition of the incident and reflected waves.

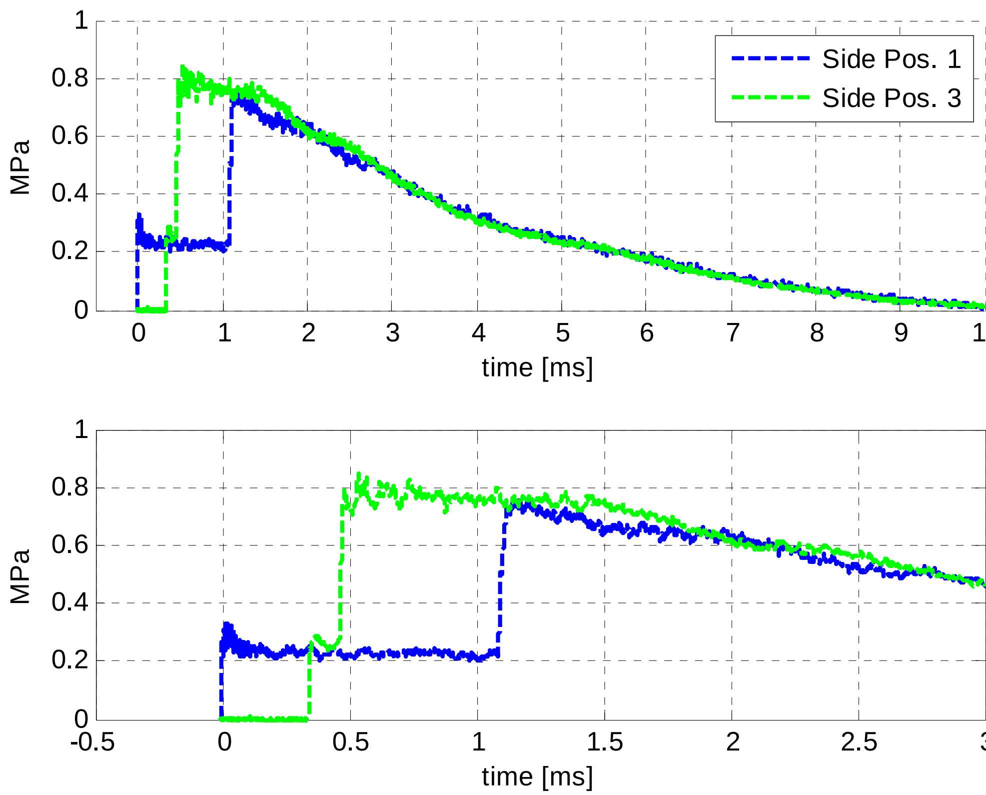



**Figure 8. Shock tube material (HD60) pressure measured from side-on pressure sensors. Top: Pressure wave for 10 ms; Bottom: Pressure wave for 3 ms**

During the shock tube demonstration test, the pressure pulse acted on the face of the striker, causing it to move towards the anvil and compress the foam test specimen. A reaction force was generated as the foam stress increased and was measured by the load cell. The approximate force on the striker was calculated from the position 3 pressure sensor measurement, which is closest to the face of the striker, and is plotted with the load cell reaction force in Figure 9. The small initial step in the approximated force from the position 3 pressure sensor was due to the timing of the incident and reflected waves, as highlighted in Figure 8. A more accurate measure of the force acting on striker could be calculated if the pressure was measured on the face of the striker, but this is not possible with this experimental set-up.

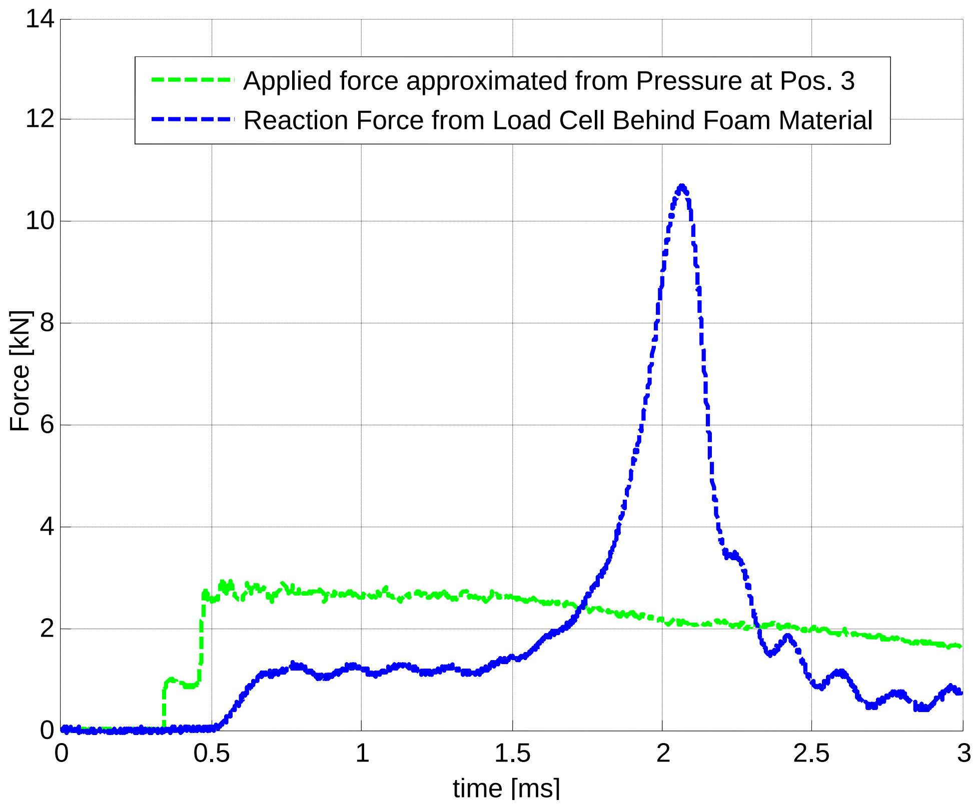



**Figure 9. Shock tube force and foam material (HD60) reaction force**

The force imbalance on the striker caused it to accelerate and increase in kinetic energy while compressing the foam. The striker velocity was calculated by integrating the acceleration data over time and was used to calculate the kinetic energy (*KE*) with the mass of the striker (*m*) with equation 1. The striker displacement (*x*) was calculated by integrating the velocity over time, and was used with the load cell data (*F*) to calculate the energy absorbed by the foam material ($E_{absorbed}$) as shown in equation 2.

$$KE = \frac{mv^2}{2} \tag{1}$$

$$E_{absorbed} = \int F dx \tag{2}$$

Figure 10 plots the kinetic energy of the striker and the energy absorbed by the foam with respect to time. The foam continues to absorb energy until the kinetic energy of the striker is zero. In the case of an partially elastic material, some of the absorbed energy is returned to the striker, causing it to rebound away from the anvil. This is visible as the second increase in kinetic energy between 2 and 3 ms.

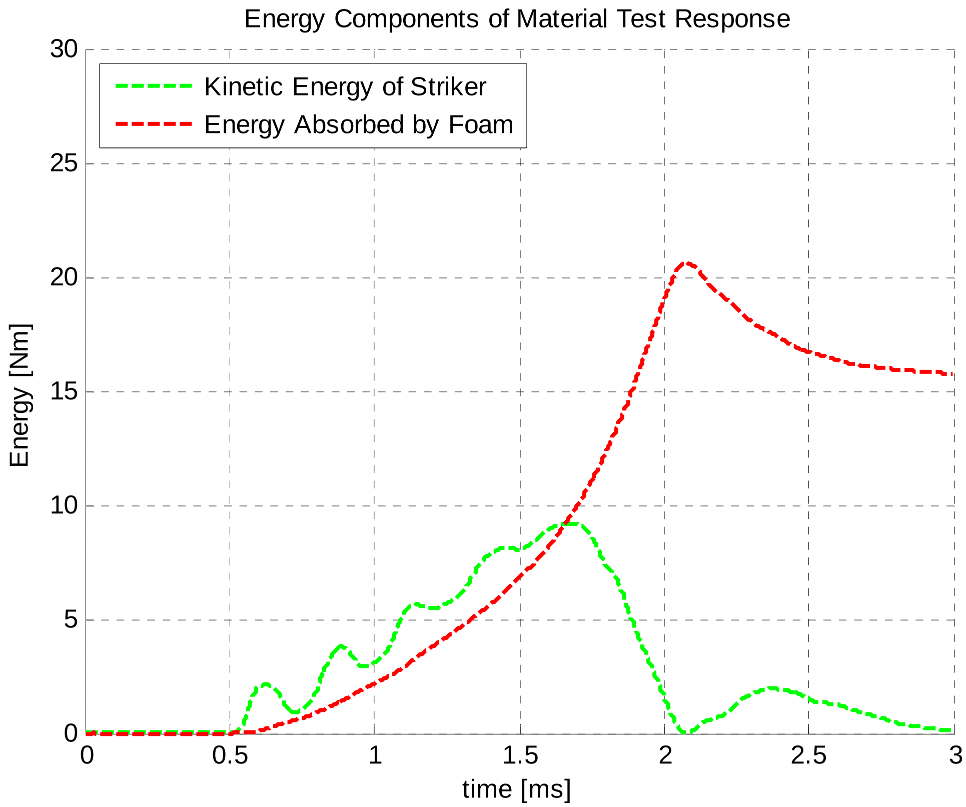



**Figure 10. Energy components of shock tube material (HD60) test response**

The plots in Figure 10 were generated from velocity and displacement calculated by integrating the accelerometer data. However, the high speed video camera can provide a more accurate means of tracking the position of the striker. Plots using both techniques to measure the strain rate vs. the strain in the HD60 foam material test are shown in Figure 11. The compressive strain is calculated by dividing the change in position between the striker and test plate by the initial thickness of the test specimen. The strain rate is calculated by multiplying the change in compression between each frame by the frame rate.

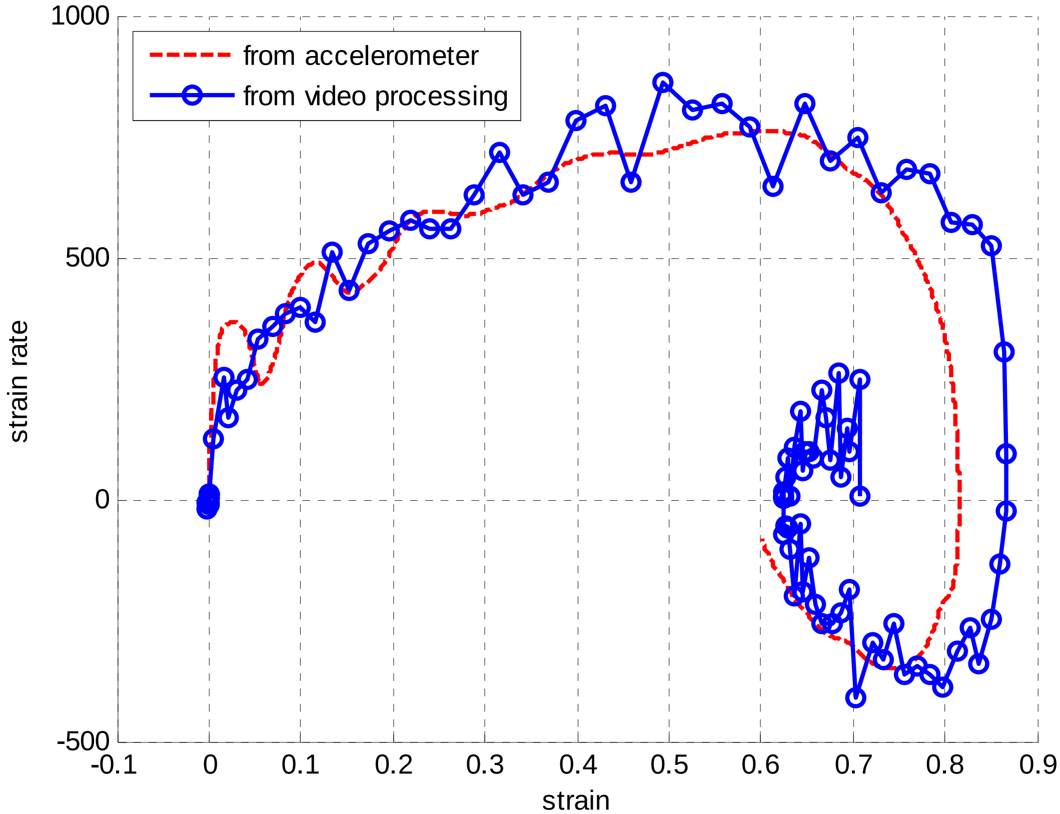



**Figure 11. Comparison of results from accelerometer and video processing measurement of shock tube material (HD60) for strain rate vs. strain during material compression**

With the foam stress calculated from the load cell measurement and the foam compression calculated from the high speed video analysis, a stress vs. strain compression plot can be generated from the material test data, as displayed in Figure 12. Each data marker in this plot shows a point at which the foam compression was calculated.

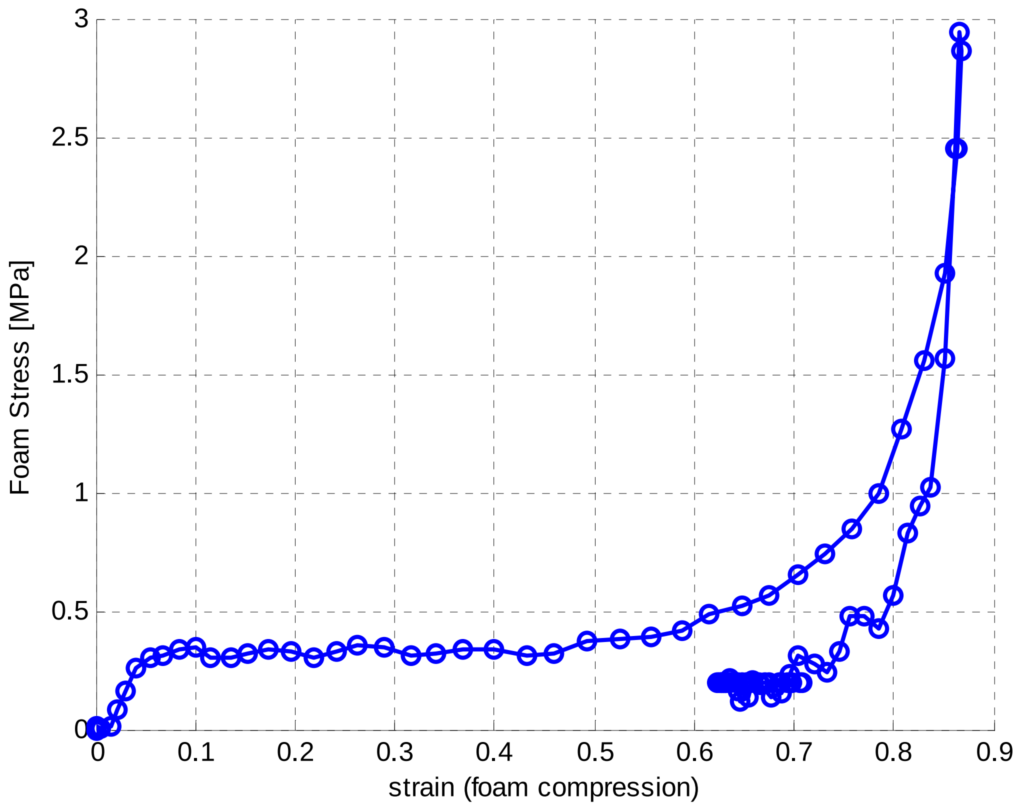



**Figure 12. Shock tube material (HD60) test: stress vs. strain**

## 5.2 *Comparison of Stress vs. Strain for All Shock Tube Tested Materials*

This section presents and compares stress vs. strain data for all the materials tested with the shock tube in this study. The higher strength materials (51A, HD80, and HD115), listed in Table 2, required a reduction in specimen surface area in order to fully compress when subjected to the shock tube pressure load. The material data in this section was reduced to show the stress at intervals of 0.05 strain, which facilitates simpler comparisons between the materials. Figure 13 shows the foam stress vs. compression for each foam material only up to 0.60 strain so the plateau stress levels can be compared.

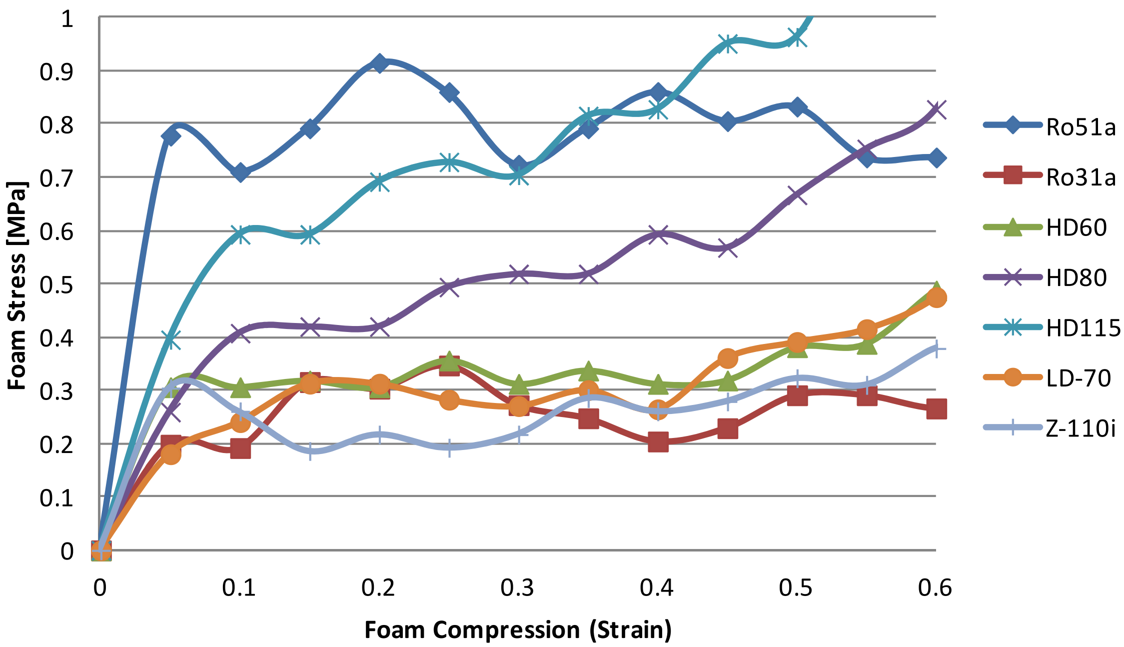



**Figure 13. All foam materials plateau stress vs. strain (response up to 0.60 compressive strain)**

The foam stress plots in Figure 13 could be used to select a foam material with the desired strength for a specific energy absorption application, such as an energy absorbing helmet liner (3). Figure 14 plots the stress vs. strain data for two densities of the ROHACELL foam (52 and 32 kg/m for Ro51a and Ro31a, respectively), which absorb energy through a cellular crushing mechanism. The shock tube material test clearly captured the constant stress plateau of the crushing response and the rapid rise in stress as the foam reached densification.

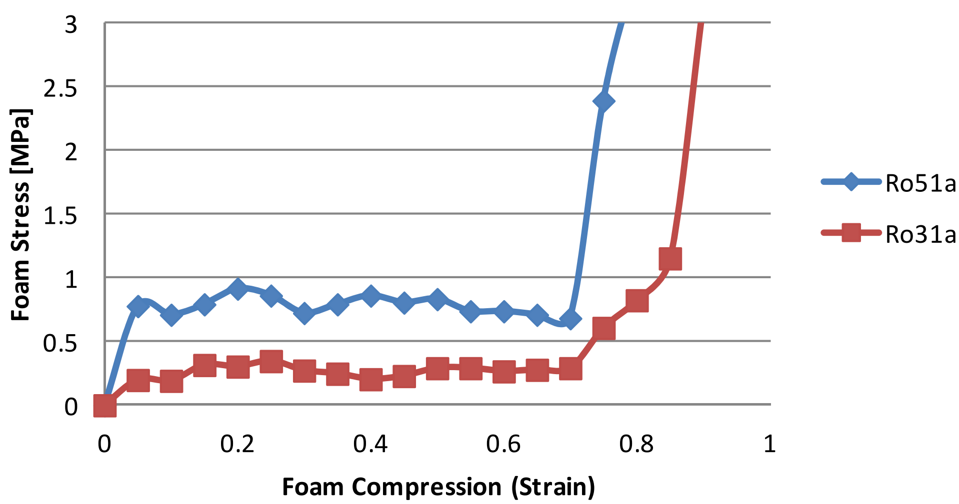



**Figure 14. ROHACELL foam stress vs. strain**

Figure 15 plots the compression response of four different types of PLASTAZOTE closed cell polyethylene (PE) foam. LD70 is a low density PE foam material, and HD60, HD80, and HD115 are high density PE foam materials. The cellular structure in these foam materials bends and buckles through elastic and plastic deformation. The gas trapped in the cells is compressed during deformation, and this contributes to the total foam stress. The foams of higher density

(HD80 and HD115) will reach the densification region earlier than foams of lower density (LD70 and HD60), and this is clearly reflected in the shock tube material test data.

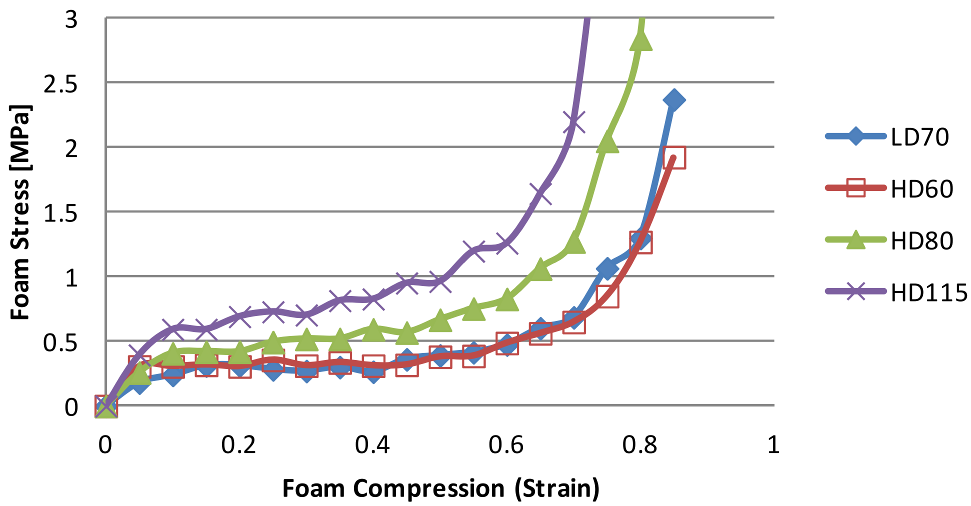



**Figure 15. PLASTAZOTE foam stress vs. strain**

## 5.3 *Comparison of Shock Tube and Drop Test Results for Selected Materials*

Ultimately, the shock tube material test provided test data which is very similar to the material test data obtained in a drop weight impact test (3). The shock tube test is conducted at a variable strain rate: the striker starts from rest, is accelerated by the shock tube air pressure, and then decelerated by the reaction of the foam response. In the drop test, the striker begins to compress the foam with an initial velocity, and is decelerated by the foam during impact. There are also some shortcomings with the shock tube material test as it is currently constructed. The striker can become misaligned as it is pushed out of the tube to compress the foam. The current system has a maximum driver pressure of 1.4 MPa, creating a reflected pressure on the striker of approximately 0.8 MPa. For the higher strength materials tested in this study, the force of the striker was not great enough to compress the foam material, unless the size of the test specimen was reduced to decrease the area of the foam. With a test specimen of significantly reduced surface area in comparison to the striker, misalignment of the striker is more likely and can become problematic. This can be seen in the comparison of the shock tube and drop test material responses of ROHACELL 51A in Figure 16. The change in slope in the densification region of the shock tube test was a result of the striker misalignment as it compressed against the anvil.

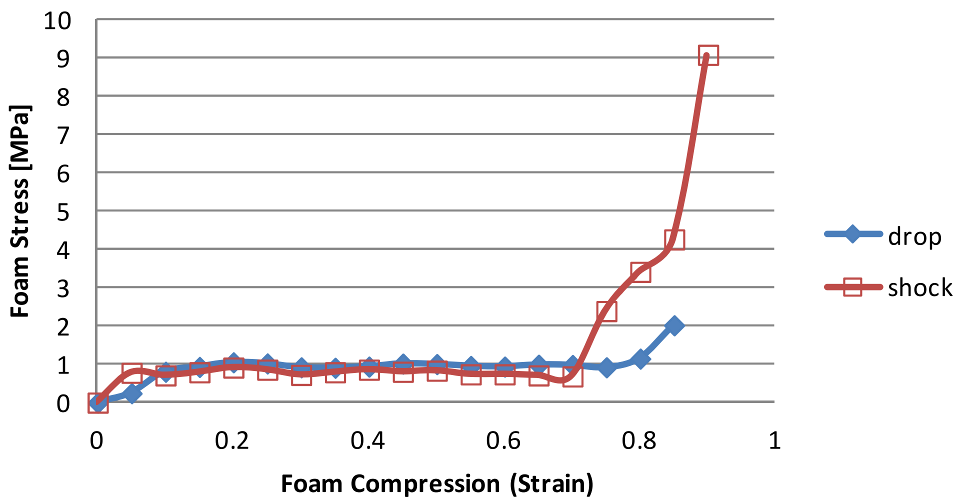



**Figure 16. Comparison of shock tube and drop tests for ROHACELL 51A stress vs. strain**

The shock tube and drop test data for the HD60 foam are compared in Figure 17. The foam test specimen was approximately the same size as the shock tube inside diameter. In this case, the shock tube and drop test data show a nearly identical response.

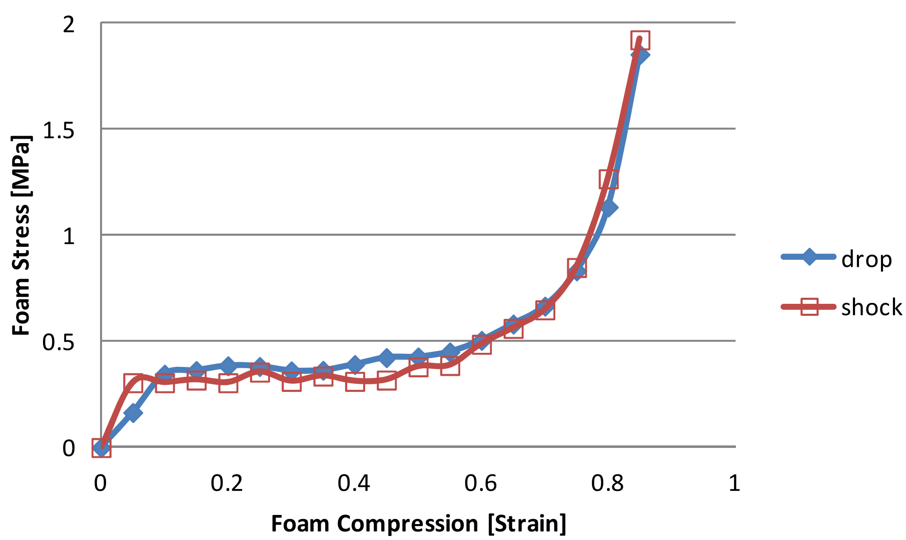



**Figure 17. Comparison of shock tube and drop tests for PLASTAZOTE HD60**

Zorbium 110i is a viscoelastic polyurethane foam which shows strain rate dependent behavior when compressed. This is displayed by the significant difference in response between a quasistatic compression test and the drop test, as shown in Figure 18.

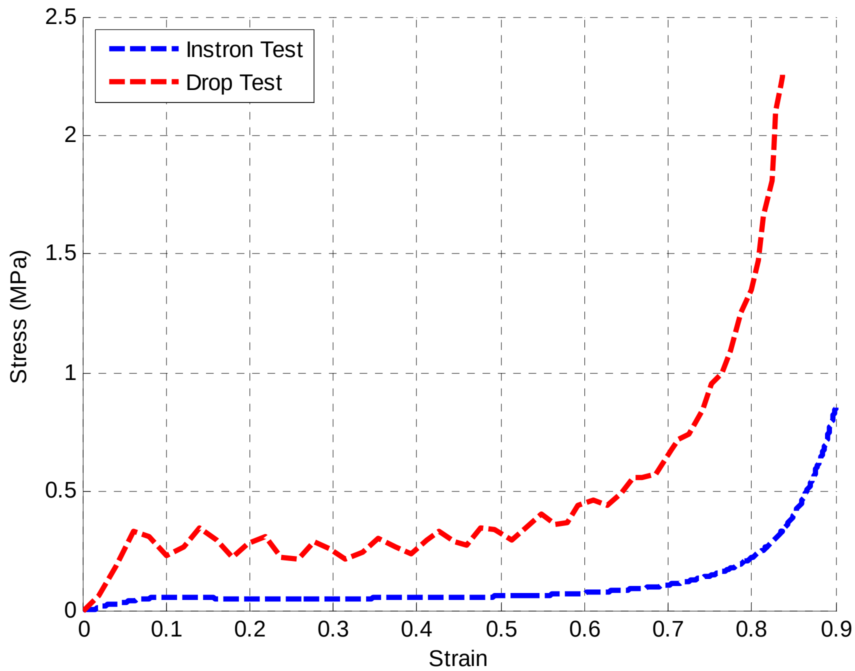



**Figure 18.  Quasistatic Compression vs. Drop-Test Comparison: Z-110i**

The strain rates vs. strain in the drop test and shock tube material tests are plotted in Figure 19. The strain rate of the shock tube test was up to four times the strain rate of the drop test, although it initially starts from rest.

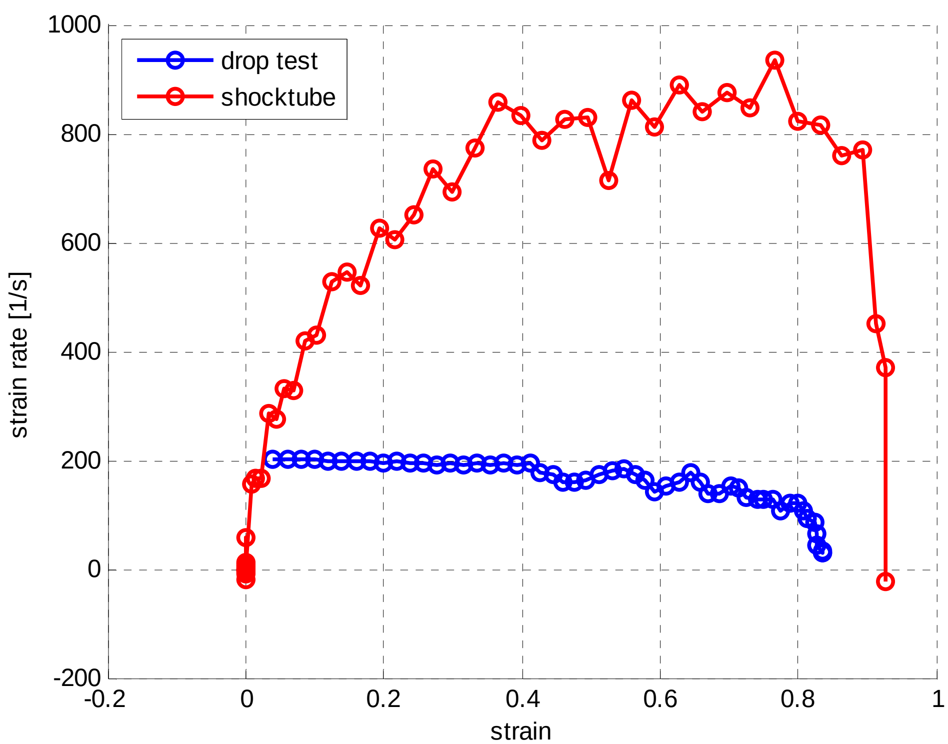



**Figure 19.  Comparison of shock tube and drop tests for Zorbium 110i foam strain rate vs. strain**

The drop test and shock tube material test responses are plotted in Figure 20. Despite the difference in strain rate and the strain rate dependence of the viscoelastic polyurethane foam, the stress vs. strain results for these tests were also very similar. For the Zorbium 110i foam and all other materials tested in this study, the difference in strain rate between the shock tube and drop test does not result in a significantly different response. Other materials could certainly show different results from these two test methods, if the materials are sensitive to strain rate changes within this range.

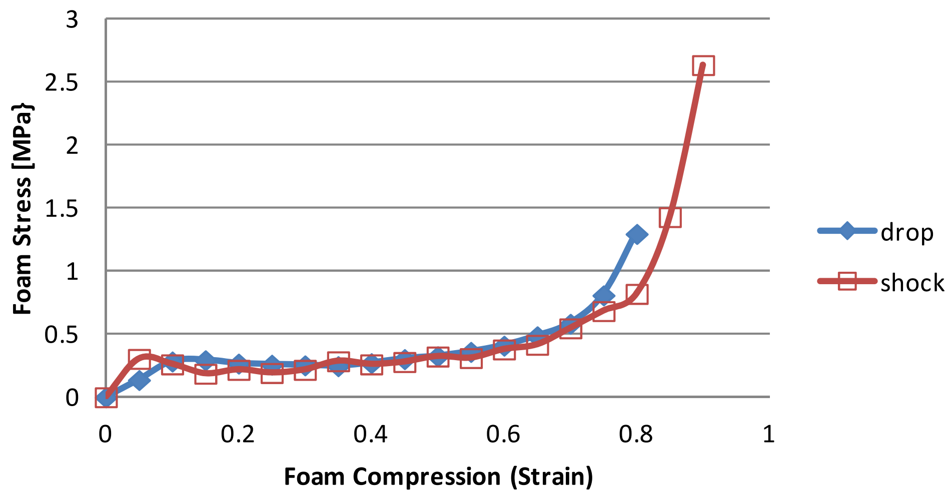



**Figure 20. Comparison of shock tube and drop tests for Zorbium 110i stress vs. strain**

# 6 Conclusions

The NSRDEC shock tube material test was presented and demonstrated in the testing of several polymer foam materials that are of interest for impact attenuation. The foam materials were rapidly compressed between the striker and a fixed test plate at dynamic strain rates reaching peak levels between 500-1000/s.  The experiment includes measuring the foam stress with a load cell and measuring foam compression with high speed video image analysis.  The results were analyzed to produce stress vs. strain compression data for each of the materials. The results were compared with data from a drop weight impact test, which utilized the same load cell and high speed video imaging techniques as used in the shock tube tests.

For the foam materials tested in this study, the shock tube and drop test experiments (3) showed very similar results.  Other materials which are more sensitive to strain rate differences within this range could certainly show different results.  In future work, adjustments to the driving pressure, striker mass, and foam thickness would affect the strain rate and could be used to study the material response at  higher rates.

This document reports research undertaken at the U.S. Army Natick Soldier  Research, Development and Engineering Center,  Natick, MA, and has been assigned No. NATICK/TR- 13/029 in a series of  reports approved for publication.

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